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Brian Kamer	0.00	
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Jean-Claude Diels	0.00	
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Technology Transfer

Microscopic analysis of filaments

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Contents

1 Abstract

This is the report on work to build a dual electron ion imaging system. Our main goal is to use this apparatus, beyond its standard operation as single ionization imaging, to capture the plasma and plasmonic forces and the contribution of field redistribution on the momentum of ejected electrons. In this apparatus the free electrons liberated by the laser pulse are removed from the interaction region with a strong repelling DC field. As they leave the interaction region their motion is driven by the static electric field towards a micro channel plate. The image is recorded with a CCD camera looking at the phosphor plate that converts the electron current to light. In our new design of VMI with additional plate, the resolution $\Delta E/E$ has improved ten times over that of the traditional design of Eppink [1].

2 Objective

The objective of this work compliment the ARO funded MURI program entitled "Filaments Science", of which J.-C. Diels and L. Arissian are the principal and co-principal investigators. The upgrade will give us a unique capability to study the interaction of light ant atoms/molecules in a filament at a *molecular-atomic* level. The acquisition of an improved aerodynamic window coupled to an electron velocity imaging apparatus will make it possible to understand, from the distribution of momentum of the electrons produced in the filament, the complete coherent re-emission of the matter, including at the light frequency (index of refraction) and other frequencies (ex. harmonic generation, THz generation).

Filament studies are traditionally performed in gas cells and atmosphere. Although the ultimate application of filaments are in a free space, the clear understanding of mechanisms that generates the supercontinuum or plasma emission can be done with microscopic studies of these emissions in a chamber. Recently there had been reports that "air lasing" is due to electron recollision in neutral and ionized molecular nitrogen in air, this claim and many other properties of filaments can be monitored with imaging electron velocities in two and three dimension. This study starts from exploring the electron current from atoms and molecules and will be extended to plasma and nanoparticles. The modification of current due to space charge effect can be visualized in these images. In our particular design the velocity imaging is no longer limitted to gas jets, an aerodynamic window with supersonic flow of air acts as a wall between our vacuum chamber and atmospheric air. This design enables us to measure the filaments directly as they are launched in a vacuum chamber.

3 Technical discussion

3.1 Status of filament research

Tinny "pits" were observed in mirrors placed in the path of an initially uniform high power laser beam, at several meter from the source. This laser damage was attributed to a nonlinear propagation effect in air of femtosecond near-infrared [2] and ultraviolet [3] pulses. This phenomenon, dubbed "filamentation" has been he object of intense research ever since, and given birth to a biannual international conference series. What was initially perceived as a minor annoyance (pits in a mirror) turned into a major research area.

Laser Filamentation is among the most fascinating topics in light and matter interaction where the optical pulse is modified due to propagation in plasma. Most often, in studies of light matter interaction, the result of the interaction is a modification of matter. An electron, an ion or a photon that is generated by ionization, or a high harmonic photon that is generated, are the tangible measurements that allow us to reconstruct the scene of the interaction. After the laser pulse has been sapped by the interaction, it is often ignored. In filament studies however, the generated plasma leaves its imprint on the optical pulse itself. A modified index of refraction due to a contribution of chemical bonds, free electrons, and ions creates a waveguide for the light to propagate beyond the Rayleigh range. As the laser pulse forms and modifies the plasma, it is in turn modified by the plasma.

The shear number of physical phenomena associated with the filaments, such as conical emission, THz emission, harmonic generation, spatial replenishment [4] self-healing [5], *etc* ... made this field rich of physics and potential application, but considerably more complex than anticipated. To add confusion to the interpretation, there is an obscure curtain of the order of a meter that separates the prepared initial condition from the observed filament. Substantial temporal [6, 7] and spatial [8, 9] reshaping of the initial pulse profile takes place in amplitude and phase, such that the pulse ultimately reaching a self-focus of the size of the filament is very different from the macroscopic beam launched in the atmosphere. In addition, we have shown that the state of polarization of the beam is changed during the process of self-focusing that precedes filamentation [**?**, 10].

We have been able to make deterministic initial conditions for the filaments by launching from a vacuum beam waist into the atmosphere. Filaments prepared in this method result from a balance of self-focusing and de-focusing, consistent with the description of Akhmanov [11], where the pulse energy is trapped in a self-induced waveguide. While considerably simplifying the theoretical modeling by eliminating the contribution from pre-filamentation shaping, that of an "energy reservoir" and that from "axicon focusing", the interaction of light and matter in the filament core is more complex than that provided by a "Drude model" and the corresponding index of refraction. During the ultrashort pulses used the 800 nm filaments, electrons generated through tunnel ionization follow a deterministic path dependent on the state of polarization of the light. There is no longer a assembly of oscillating dipoles that radiate back into the applied field, but, in addition to the index contribution of the neutral molecules, the fields from the moving/accelerating positive ions and electrons that has to be taken into consideration.

3.2 Why do we need to image the velocity of electrons ?

Electron currents are the main source or radiation in filaments. Knowing the trajectory and acceleration of the electrons in the field of the filament, it is possible to calculate the radiation that is produced by the moving electron. This radiation includes a spectral component which will be in phase (absorption) or in quadrature (index of refraction contribution) with the optical radiation. Lower frequency components are representative of the THz radiation being produced by filaments, as demonstrated recently by the PI [12]. The nonlinearity of the motion will also result in harmonic generation. The study of electron currents is thus a key to the analysis of radiative phenomena associated with filaments, and to modeling the difference of response in linear or circular polarization.

3.3 What is VMI?

VMI stands for velocity map imaging (VMI) is a spectrometer similar to cold target ion recoil momentum imaging COLTRIMS. Both devices are extensively used to understand ionization and chemical process in molecular level. Both techniques are based on similar working principles. Physical or chemical processes in a target are triggered either by particle impact or by the interaction with a light field, which results in charged fragments. The processes involved can include any form of direct or indirect ionization, dissociation, or even a chemical reaction. The charged fragments (ions and/or electrons) are accelerated in a dc electric field onto a two-dimensional 2D detector where they are registered as

events. Their positions and/or arrival times are recorded, giving insight into the angular and kinetic energy distribution.
VMI (see figure 1 a)is a high resolution ion or electron imaging technique. The technique is similar to x-ray diffraction in which the imaging is in the momentum space rather than the configuration space. Electrostatic optics, usually consisting of a flat repeller plate, a flat apertured extractor plate, and a flight tube with another flat plate at ground are used. The geometry of these parts and the applied voltages determine the fragments' path of flight toward the detector. Their lateral displacement on the detector upon arrival is defined by the initial velocity vectors perpendicular to the detector axis. A unique feature of VMI lies in decoupling the position of creation of the fragments from their impact position on the detector by using an electrostatic lens. In this way, spatial blurring of the image is minimized and a velocity resolution of less than 1% can be achieved.

In order to expand the dynamic range of this imaging we extended the imaging lenses to four. Simillar to imaging objects in the configuration space, here havig multiple lenses expands the dynamic range and magnification. In VMI system the plates are fixed in position and only voltages are adjustable. The first parameter to calculate for each geometry is the ratio between the voltage plates to obtain a clear image on MCP. The charged particle trajectory can be monitored with SIMION software. SIMION is a software package primarily used to calculate electric fields and the trajectories of charged particles in those fields when given a configuration of electrodes with voltages and particle initial conditions, including optional RF (quasistatic), magnetic field, and collisional effects. The initial velocity of the charged particle is determined by the ionized particle, laser field and polarization. The DC voltages in the vaccum chamber is set to repell to charged particle (electron or ion) and guide them to imaging screen which is a phosphorus screen , MCP and finaly a CCD for digitally recording the image. The first step in the design is to simulate particle trajectory, the result of such simulation is presented in figure 1. Figure 1 (a) shows the Eppink geometry [1] The electrostatic lensing is visualized by looking at potential contours when proper ratio of 0.71 is applied between extractor and repeller plate as shown in figure 1(b).The new design with plate distances and opening is presented in figure 1(c) with proper ratio between the plates to operate in the imaging mode figure 1(d).

Some of the detailed consideration of imaging is presented in Fig. 2. Figure 2 (a) shows how electrons with various energies will end up on different spots on the MCP using Eppink geometry. The size of the MCP defines the dynamic range. Note that the resoultion varies across the image, as is presented in figure 2 (b) . The spot size for particles varies across the energy range. To calculate the spot size the ionized particles with the same azimuthal velocity are released from the interaction region to the imaging screen. The size on the phosphorus screen is referred as a spot size. Note that the main limitation factor is usually the CCD pixel size. Figure 2(c) Shows the spot size for selected ratios of the wo plates with respect to the repeller plate and Figure 2(d) shows the spot displacement with 1 eV variation comparing Eppink geometry with our new VMi design.

In order to have a functional imaging system various equipments are needed, a schematic of a VMI system is shown in Figure **??**. Figure 4shows the picture of the electrostatic lens on the left and the assembled system on the right.

4 Aerodynamic window

The aerodynamic widow is a supersonic flow of air that serves a boundary between vacuum and the atmosphere. It makes it possible to prepare various field configurations in vacuum, and project them into atmospheric air in order to determine which initial condition leads to a stable filament.

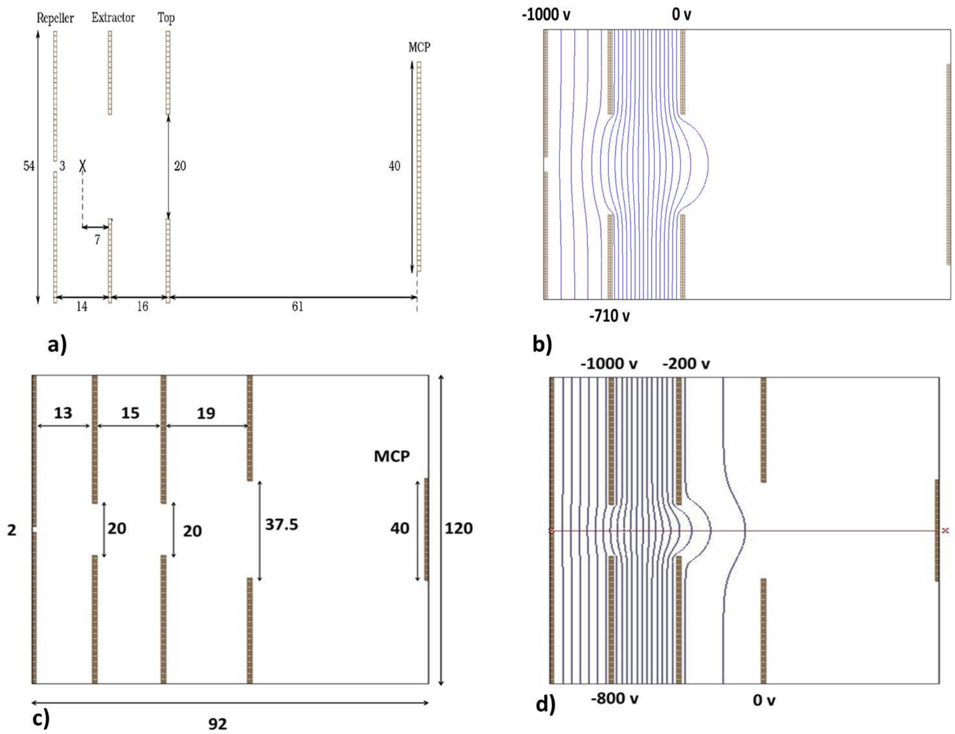

Figure 1: a) Eppink's Geometry (dimensions in mm) b) Simulation of potential contours with software SIMION 8.1 for traditional VMI geometry of Eppink c) The new proposed VMI geometry adding a forth plate (dimensions in mm) d) Potential contours simulation with software SIMION 8.1 for modified VMI.

A new aerodynamic window is designed and built to connect filaments to the VMI system. In this configuration the laser beam is sent through the repeller along the axis of the symmetry of the electrostatic lens. The aerodynamic window provides a transparent wall between atmospheric air and the 10^{-5} torr pressure in the detection chamber. The ionization of samples in the detection system will reveal the laser field properties such as intensity and polarization.

Figure 5 shows the pressure gradient in the aerodynamic window and

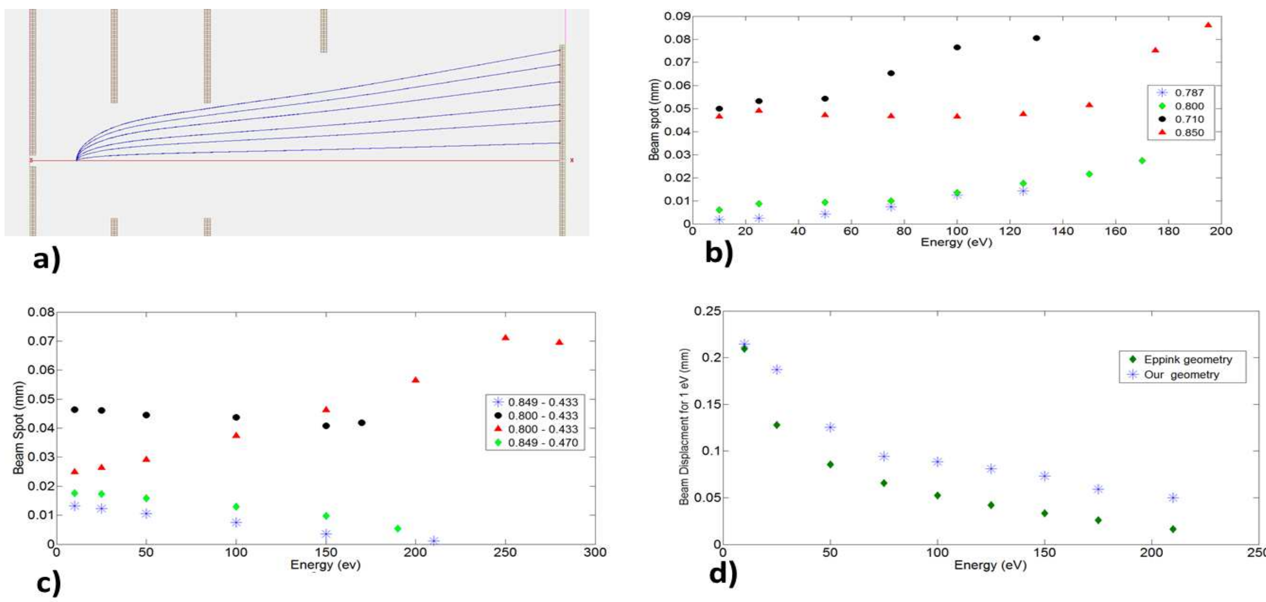

Figure 2: a)Simulation of electron trajectories in energy range of 10 to 210 eV all releazed with 90^0 azimutal velocity with respect to electrostatic field axis with the voltage settings of figure 1-c b) Simulation of image spots on MCP as a function of electron energy for different voltage ratios of extractor to repeller (repller fized at 10 kV). c) Simulation of beam spot vs energy for different voltage ratios of first and second lens with respect to the repeller based on our new geometry for 10 kV repeller volatge and 90^0 azimutal velocity. d) Beam displacement for 1 eV energy difference for both geometries for for 10kV repeller voltage and 90^0 azimutal velocity direction and the best ratios.

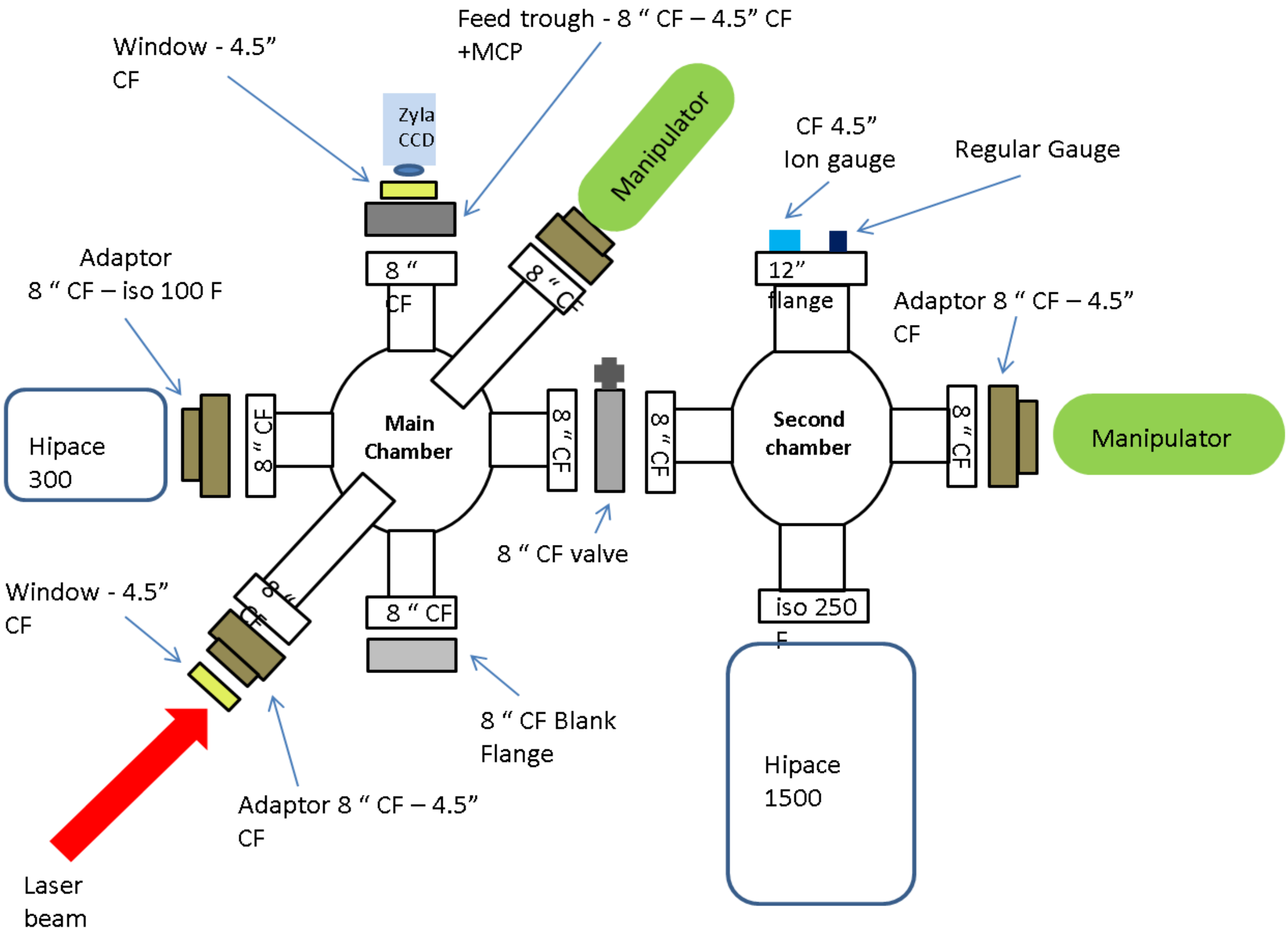

Figure 3: A schematic of our VMI system. The chamber on the right is the source chamber pumped by HiPace 1500 from pfeiffer. The left chamber is a detection chamber pumped by HiPace 300. Both turbo pumps are backed with a scroll pump. The laser beam is shown with a red arrow. It is focused with a parabolic mirror inside at the center of the chamber which is the center of the electrostatic lens. The gas is provided with a parker jet source. Manipulators are parts of the system to carefully position the jet and the focusing mirror to achieve the proper alignment. various power supplies and vacuum monitors are attached to the system (not shown).

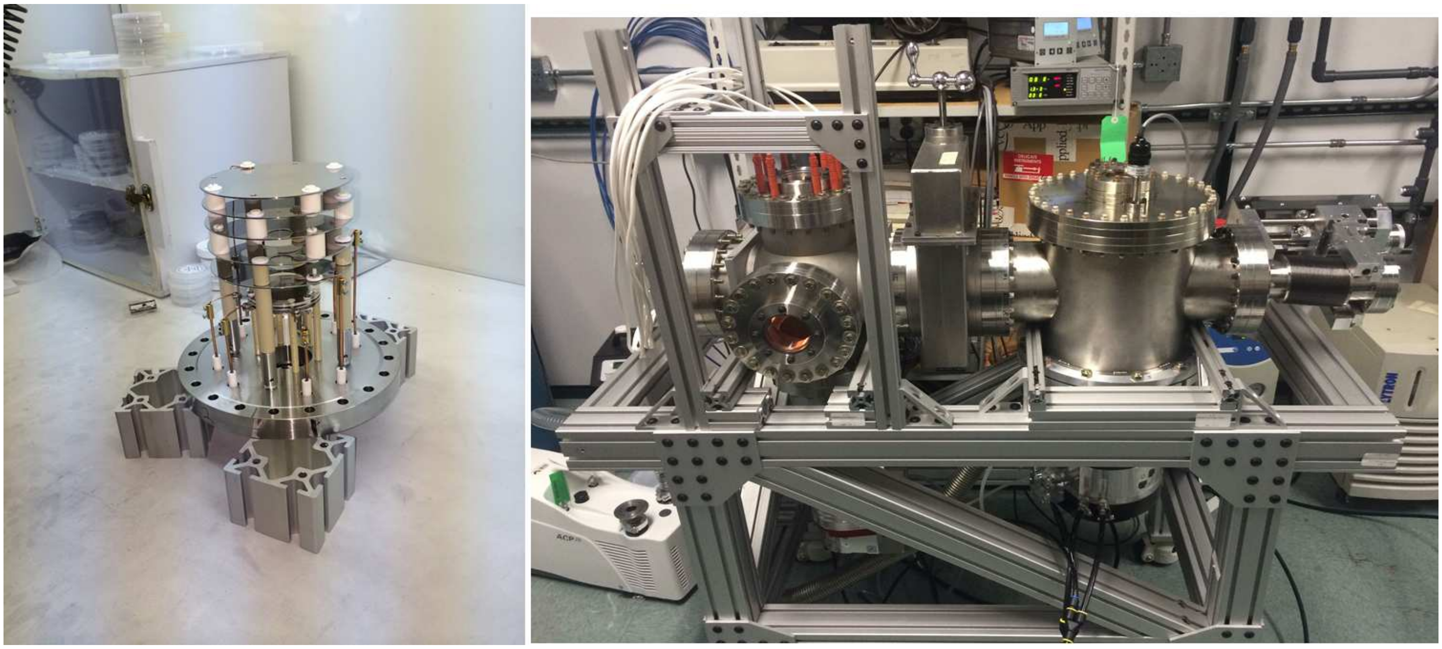

Figure 4: left) A photo taken at the time of assembling the detection system. right) The completed VMI system.

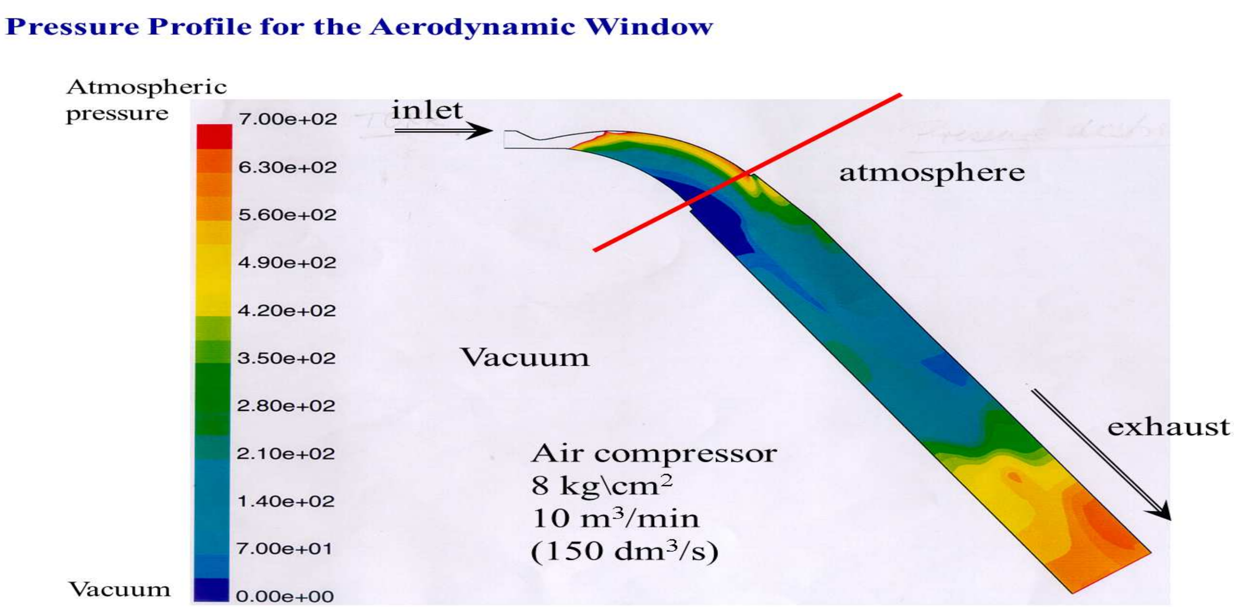

Figure 5: A graph of aerodynamic window with the pressure gradient through out the air flow volume. The red line shows the direction of the beam. The color code shows how the laser goes through the pressure gradient from atmosphere to 1 mbar (shown as zero on this scale)

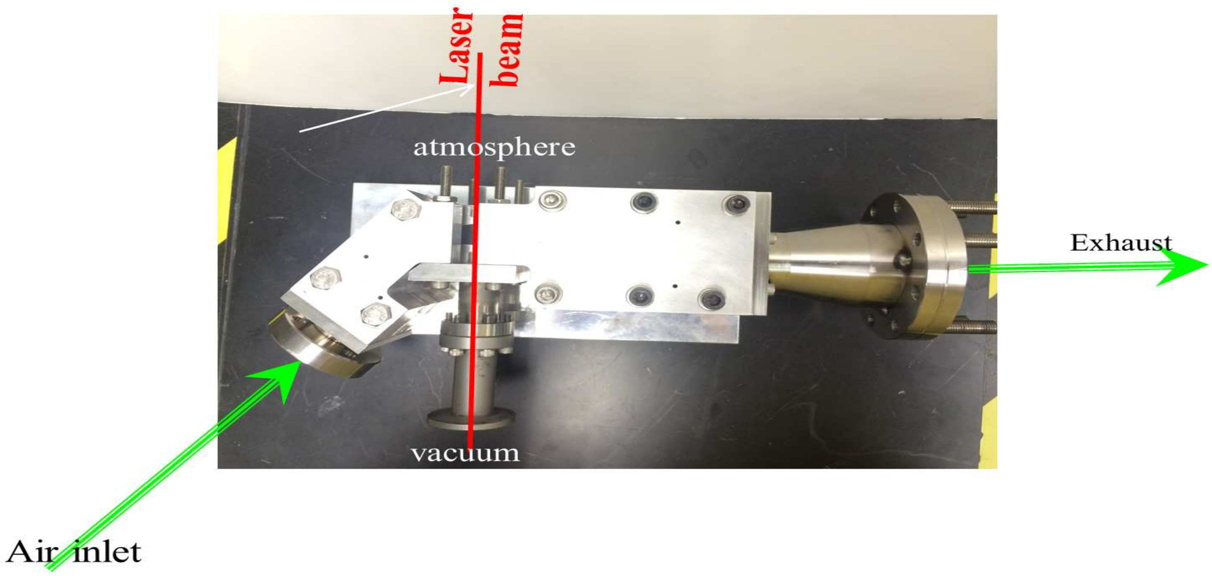

Figure 6: A picture of aerodynamic window which we built to combine with VMI system. The air flows from left to right in the exhaust line. The laser beam is shown with the red line.)

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